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DETECTING A POINT RADIATOR IN THE PRESENCE OF NONGAUSSIAN INTERFERENCE

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9

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An optimal method of detecting a pulse signal in the presence of background interference of the kind presented by cloudy sky radiation characterized by a nongaussian distribution law is described. [3

Many problems in optical location, navigation direction finding, and the like, are connected with the detection of a signal from a point radiator against a background of natural formations.

In works known to date [1-3] the effect of background interference was taken into account within the framework of correlation analysis, leading to linear methods of analyzing the electrical signal arising in the radiation receiver. Experience in the use of linear systems shows that in the case where signals are received from point objects, i.e., signals having the form of Dirac δ-functions, linear systems are least protected from the effects of interference whose values change spasmodically.

The construction of a statistically optimal system consists first of all in the selection of a background model that reflects its spasmodic structure. The simplest such model is a background model in the form of a population of spots (clouds) randomly distributed against a "clear sky" and having random (but constant within the limits of each spot) brightness values. We shall assume that in any cross section of such a background the distribution of boundaries (transitions from dark to light and back again) is similar, i.e., that the background is homogeneous and isotropic, and that the boundary distribution is Poissonian, i.e.,

$$p(n, r) = \frac{1}{n!}(\nu r)^n \exp(-\nu r), \qquad (1)$$

where p(n,r) is the probability that in the interval r will be equal to n intersections; v is the average frequency of intersections in a single segment.

It is useful to distinguish this model from the anisotropic two-level background model in the form of a "chess board," examined in works [3-4].

We shall first examine the interference signals that form during search scanning (in the case of uniform displacement of the radiation receiver along the x axis) when a background inhomogeneity boundary [4 is intersected in the assumption of ideal optics. The shortcomings of optics, or aberration distortions, we shall consider later.

We shall assume that the radiation receiver is in the form of a Hxh ($H > h$) rectangle whose angular dimensions are much less than the mean angular dimensions of the background inhomogeneity, i.e.,

$$h/H \ll 1. \qquad (2)$$

Granting this, the inhomogeneity boundary can be presented in the form of a direct boundary with inclination θ to the scanning direction. The signal received from the interference $\varphi(x)$, received as the result of boundary intersections, for a considerable part of its change is described as a linear function (as shown in figure 1, with receiver displaced from position 1 to position 2). This makes it possible to approximate its increase or decrease with a linear function throughout the entire sector of change. The signal from the point object has the form of a rectangular pulse having width h.

We shall eliminate the constant component present in the interference either by means of linear transformation or by means of a second receiver located beside the first and connected in an opposite way. Therefore the resulting signal from the interference $\Phi_1(x) = \varphi(x) - \varphi(x-h)$ is realized in a form consisting of nonintersecting isosceles trapezoids located along the abscissa (capable of degenerating into triangles) of positive and negative polarity, random extension and amplitude (but limited on top along the modulus, since maximal background brightness drops are limited) and randomly separate from each other. It is important to note that the frontal lengths of the trapezoidal formations are precisely equal to the width of the rectangular pulse.

The signal from the point object is obtained in the form of rectangular pulses of different polarity having width h adjacent in the base.

The effect of aberration distortions manifests itself in the "smoothing" of the processes obtained. As a result of this "smoothing," the rectangular pulse assumes a bell-shaped form. The function describing its change as a function of the time argument is designated $s_o(t)$ and it is assumed that at $t_1 > h/2$ $s_0(t) = 0$ Aberration distortions of optics can be treated as a kind of linear transformation, consequently, the "smoothed" interference fronts will as before have a length equal to that of signal δ and be described by functions that are integrals of $s_o(t)$.

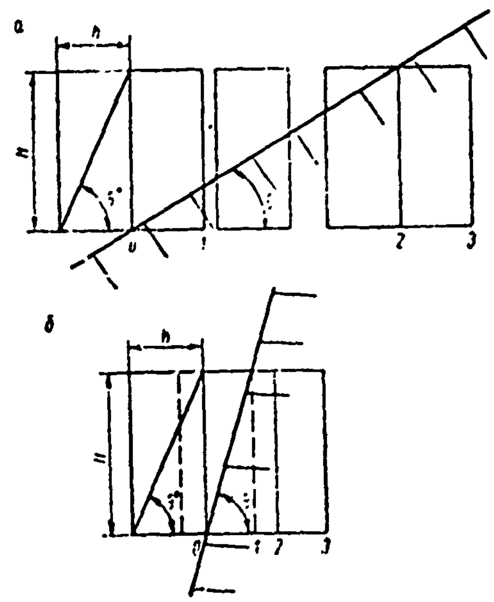

Figure 1: Change in receiver position when intersecting inhomogeneity boundary: a) $\theta < \theta^*$, b) $\theta > \theta^*$.

The random interference time function $\Phi(t)$ can be presented in the form $\Phi(t) = F(t)A(t)$, where function $F(t)$, normed to absolute maximum value, is the same type of function as $\Phi(t)$, while $A(t) > 0$ is a spasmodic process with a uniform distribution of values in segment $[o, A_{max}]$ that changes its values only at those time moments when process $F(t)$ deviates from the zero state. For ease of later computations, we shall consider that process $A(t)$ assumes only a finite number of values $0 < a_1 < a_2 < \ldots < a_p = A_{max}$; $p \gg 1$ is a whole number and

$$P(A(t) = a_i) = \frac{1}{p};\ i = 1, 2 \ldots p. \quad (3)$$

One of the possible realizations of interference $\Phi(t)$ together with functions $A(t)$, $F(t)$, and $s_0(t)$ is depicted in figure 2.

The signal from the point object will become bipolar and will be determined by function $\varepsilon s(t)$, where ε is the signal amplitude unknown to the observer.

Radiation receiver noise is considered white and normal.

Since we are assuming that the radiator, subject to detection, is a point radiator, signals from the target and background will be additive and the total signal will be determined as

$$y(t) = \begin{cases} A(t)F(t) + n(t) + s(t), \\ \text{if there is a signal, and} \\ A(t)F(t) + n(t), \\ \text{if there is not a signal.} \end{cases}$$

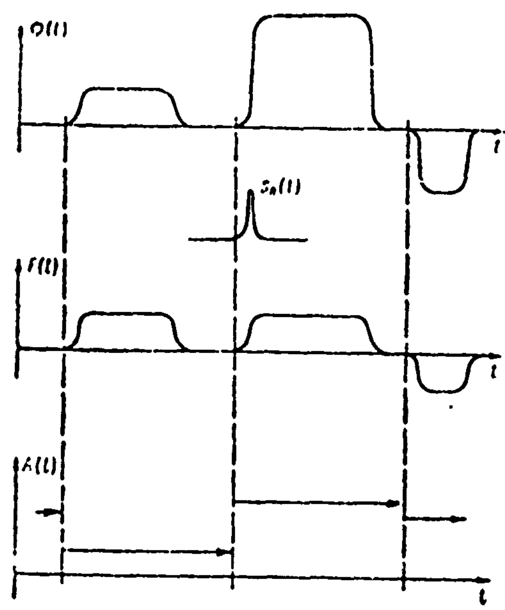

Figure 2: Realization of random functions $\Phi(t)$, F(t), and A(t).

Without disturbing the generality of the examinat on, we solve the problem in the discrete form, assuming that the observ tion of process y(t) occurs at discrete time moments

$$t_1, t_2 \ldots ; t_N; \quad t_i = t_1 + (i-1)\Delta t$$

and

$$y_m = y(t_m)$$

are values of the observed process at reference points. We shall select the separation interval so that there is a sufficient number of readings for the duration of the signal, i.e., so that $\delta / \Delta t = k \gg 1$. Receiver

noise will be given by the sequence n_j of normal, mutually independent values with parameters $(0, \sigma)$. In examining the problem in a time-discrete sense, and assuming that $k \gg 1$, it is natural to assume that both the signal arrival time and the time moments of transition of process $F(f)$ from one set of states to another correspond with selected t_i readings. Whence it follows that interference values $F(t)$ are completely determined by the set of $4k-1$ of f_i numbers, where $i = -(2k - 1) \ldots (2k - 1)$, which are computed with the formulas

$$
\begin{gathered}
f_0 = 0, \\
f_i = \int_{-\tau/2}^{-\tau/2+i\Delta t} S_0(y)\,dy \Big/ \int_{-\tau/2}^{\tau/2} S_0(y)\,dy; \\
i = 1, 2 \ldots k, \\
f_i = f_{2k-i};\ i = k+1, k+2 \ldots 2k-1; \quad (5) \\
f_i = -f_{-i}, \quad i < 0.
\end{gathered}
$$

The values

$$
\begin{gathered}
f_1, f_2 \ldots f_k \ (f_{-1}, f_{-2} \ldots f_{-(k-1)}) \quad \text{and} \\
f_{k+1}, f_{k+2} \ldots f_{2k-1} \ (f_{-1}, f_{-2} \ldots f_{-(2k-1)})
\end{gathered}
$$

correspond respectively to increasing (falling in the negative region) and falling (increasing in the negative region) interference pulse fronts; f_k and f_{-k} are extremal internal values.

The signal will be given by vector

$$\vec{s}_i = s(s_1, s_2 \ldots s_{2k}),$$

where

$$s_i = s_0(-\tau/2 + i\Delta t); \quad i = 1, 2, 3 \ldots 2k.$$

Let us study the statistical properties of process $F_m = F(t_m)$, $m = 1, 2 \ldots N$. Condition (1) indicates that the telegraphic signal, received in a random one-dimensional background cross section, is a Markov process. Process F_m by virtue of its structure resembles the telegraphic signal and differs from it only in that its fronts are smoothed and in that it takes both positive and negative values. Therefore we shall also examine process F_m as a random Markov sequence with possible f_i states and with consequent transition probabilities. From

state f_0 the only possible transition is to states f_0, f_{-1}, f_1 with probabilities α', $\alpha/2$, $\alpha/2$ respectively ($\alpha' = 1 - \alpha$). From state f_k, process F_m with probability β turns into f_{k+1} and with probability $\beta' = 1 - \beta$ remains f_k. From states f_j, where $j \geqslant 1$; $j \neq k$; $f \neq 2k-1$, with probability 1 a transition takes place to state f_{j+1}. Finally, from state f_{2k-1}, the process with probability 1 turns into f_0. Analogous relationships are true for states f_{-j}, where $j > 0$.

Since A_r and F_r in the aggregate form a Markov process, the 3-dimensional vector

$$\vec{w}_r = (y_r, A_r, F_r)$$

also forms a Markov process. Therefore the detection problem obtained here in discrete form fits totally into the problem scheme used in the detection of a weakly determined signal, examined in reference [5]. In accordance with the result obtained in reference [5], the optimal receiver consists of circuits connected in series, located right after the unit to eliminate the constant component of interference. [6

1. Of a nonlinear transformation effecting "identification" of the interference and transforming input realization y_r into the sequence

$$y_r^{*} = y_r - E(\Phi_r \mid \vec{y}_r) = y_r - E(A_r F_r \mid \vec{y}_r)$$
$$= y_r - \sum_{i=1}^{p} \sum_{j=-(2k-1)}^{2k-1} a_i f_j w(a_i; f_j \mid \vec{y}_r), \qquad (6)$$

where vector

$$\vec{y}_r = (y_1, y_2 \ldots y_r);$$

the estimate of the current interference value

$$E(\Phi_r \mid \vec{y}_r)$$

is the conditional expection value Φ_r, computed on the basis of all observations known to the current time moment and in the assumption that the signal is absent;

$$\omega(a_i;\ f_j \mid \vec{y}_r) = P(A_r = a_i;\ F_r = f_j \mid \vec{y}_r)$$

are a posteriori probabilities determining the conditional expectation

$$E(\Phi_r \mid \vec{y}_r).$$

2. Of a linear filter consistent with the form of the signal received.

3. Of a threshold unit.

The nonlinear transformation (6) plays the major role. Since vector (y_r, A_r, F_r) is a Markov process, the a posteriori probabilities that figure in (6)

$$\omega(a_i;\ f_j\ \vec{y}_r);\ i = 1, 2 \dots p;$$

$$j = -(2k-1) \dots (2k-1)$$

form a conditional Markov process [6]. This very important property makes it possible to determine the conditional probabilities without the need of remembering all the current values of vector y_r. The method of computing these probabilities has been quite well developed [6] consequently, omitting intermediate calculations, we shall give the final relationships

$$\omega(a_i;\ f_0 \mid \vec{y}_r) = \frac{Q(y_r - a_i f_0)}{l_r}\,[\alpha' \omega(a_i;\ f_0 \mid \vec{y}_{r-1}) +$$

$$+ \omega(a_i;\ f_{(2k-1)} \mid \vec{y}_{r-1}) + \omega(a_i;\ f_{2k-1} \mid \vec{y}_{r-1})];$$

$$\omega(a_i;\ f_{\pm 1} \mid \vec{y}_r) =$$

$$= \frac{\alpha Q(y_r - a_i f_0)}{2p l_r} \sum_{j=1}^{p} \omega(a_j;\ f_0 \mid \vec{y}_{r-1}), \qquad (7)$$

$$\omega(a_i;\ f_{\pm l} \mid \vec{y}_r) = \frac{Q(y_r - a_i f_{\pm l})}{l_r}\,\omega(a_i;\ f_{\pm(l-1)} \mid \vec{y}_{r-1});$$

$$l > 1;\ l \neq k;\ l \neq k+1.$$

$$\omega(a_i;\ f_{\pm k} \mid \vec{y}_r) = \frac{Q(y_r - a_i f_{\pm k})}{l_r}\,[\omega(a_i;$$

$$f_{\pm(k-1)} \mid \vec{y}_{r-1}) + \beta' \omega(a_i;\ f_{\pm k} \mid \vec{y}_{r-1})];$$

$$\omega(a_i;\ f_{\pm(k+1)} \mid \vec{y}_r) = \frac{\beta Q(y_r - Q_i f_{\pm(k+1)})}{l_r}\,\omega \times$$

$$\times (a_i;\ f_{\pm k} \mid \vec{y}_{r-1});$$

where $Q(x) = (2\pi\sigma^2)^{-1/2} \exp - \frac{x^2}{2\sigma^2}$,

while the norming factor I_r is determined from the equation

$$\sum_{i=1}^{p} \sum_{j=-(2k-1)}^{2k-1} \omega (a_i; f_j | \vec{y}_r) = 1. \qquad (8)$$

As seen from (8) and (9), the a posteriori probabilities

$$\omega (a_i; f_j | \vec{y}_r)$$

are computed recursively from the current observation of y_r and from the values of these same probabilities found for the preceding time moment r-1.

Analysis of the sensitivity and anti-interference capabilities of the detection procedure proposed is beyond the scope of the present article.

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